A 1 MV, 5 Hz, 8 CHANNEL WATER SWITCH

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Abstract

An extension of previous work by J.C. Martin and workers at Sandia National Laboratory (SNL) has successfully resulted in a high-power, repetitively pulsed, water switch. We have demonstrated a 1 MV, 5 Hz, multi-channel switch which transferred nearly 1 kJ per pulse.

Using a capacitive peaking circuit switched by a single channel water arc, the peaking capacitor and the multi-channel switch were pulse charged in 15 ns (10% to 90%). Both switches were untriggered. Current risetimes better than 2.5 ns were observed in the multi-channel switch. A simple coaxial $\dot{D}$ probe mounted in the switch was utilized to measure the current risetime and to infer the gap breakdown field of 1.1 MV/cm. The switch gap, risetime and number of channels are consistent with calculations from the relationships of J.C. Martin.

Although not quantitatively investigated, significant erosion and temperature effects were observed. Both switches were operated repetitively at 5 Hz for 150 second bursts. The repetition rate was limited by the power supply while the burst lengths were limited by other system failures. Improvements in the experiment may extend the repetition rate and burst length to greater than those observed by better materials choices and design.

Introduction

Pulsed power systems with deionized water dielectric energy storage may utilize a water switch to great advantage. Elimination of insulating gas/water interfaces improves both the speed of the switch through a lower electrode inductance and the reliability against insulator failure. Until now, it was thought that a water switch was inherently single shot at moderate (kJ) energies.

We have shown that repetitive switching with water is possible at an energy of nearly 1 kJ. Due to efficiency considerations, at least for untriggered switching, repetitive water switching is most suitable for the final stage in pulse compression. It is in this stage (< 30 ns charging time) that the best risetimes are achievable with consequently lower energy loss in the switch. Unfortunately, the shock induced breakdown of water causes significant electrode erosion which may be more of a limit to repetitive switching than the properties of the water itself.

If high power water switches can be operated at the repetition rates demonstrated by gas switched systems, they represent an excellent alternative for compact pulsed power systems.

Circuit and Switch Description

The compact pulser (Fig. 1) used to test the multi-channel switch consisted of a 50 kV, 0.8 μF primary capacitor switched into a 25:1 spiral wound pulse transformer. The transformer was
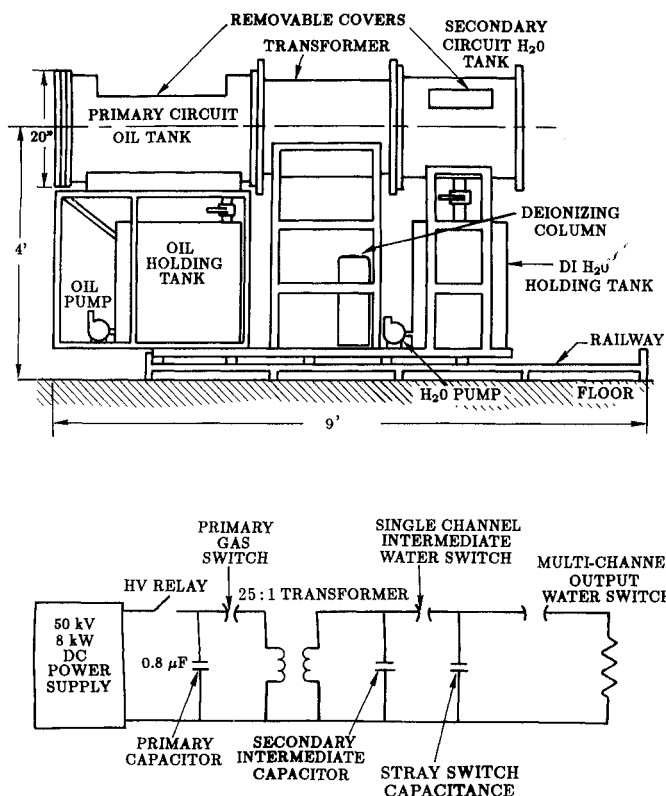

Figure 1. Compact 1 MV pulser.

operated in dual resonance.[1] An intermediate, flat, water capacitor (8 Ω) of 900 pF provided the secondary capacitance for the transformer and was discharged through a single-channel water switch into the multi-channel switch. This switch consisted of a cylindrical plate with 8 adjustable stainless steel pins which

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discharged to ground. (See Fig. 2.) A stray capacitance of 300 pF for the 8 channel switch was calculated using the code JASON. The estimated switch impedance was 6 Ω. Energy
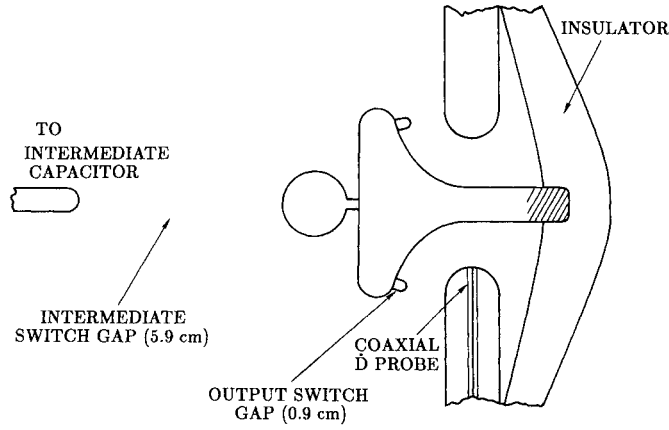

Figure 2. Two-stage repetitive water switch.

trapped and dissipated in the intermediate switch (> 100 J) and the impedance mismatch between the capacitors prevented achieving any ringing gain. The observed transformer efficiency was better than 90%. At least 900 J then were discharged to ground through the two switches.

Switch Results

A calibrated coaxial $\dot{D}$ probe was mounted in the multi-channel switch.[2] This allowed observation of the field across the switch during the 15 ns (10%–90%) charge time and the discharge time. Current rise times less than 2.5 ns were observed. Integration of the $\dot{D}$ signal indicated a breakdown voltage of 1 MV. Shown in Fig. 3 are the raw $\dot{D}$ signal from a LeCroy 6880 digitizer and its integral. Because the $\dot{D}$ response is proportional to the current in the switch stray capacitance while the electrode is brought to full voltage, its time integral is proportional to the field in the region of the probe. From the $\dot{D}$ trace it is seen that the field builds up for approximately 26 ns before the gap breaks down. The intermediate capacitor and output switch act like a voltage peaking circuit with an oscillation period of 60 ns. At 16± 4 MHz, the $\dot{D}$ probe attenuation in water was measured to be 75 dB. For the example in Fig. 3, a voltage of 985 kV in the probe region was inferred. Because the wave transit time from the probe region to the gap region is a small fraction of the 26 ns charge time, the gap voltage was approximately 1 MV.

Recognition of the difficulty associated with an accurate determination of the gap voltage in such a compact geometry demands some corroboration of the above results. The empirically determined streamer velocity relationships of H.G. Herbert[3] and breakdown electric field strengths of J.C. Martin[4] for water dielectrics have been verified,[5] reverified,[6] and scaled with reasonable accuracy. For an enhanced anode (necessary with a dual-resonance, transformer-driven, two-stage, water-switched network), the average streamer velocity determined by Herbert is

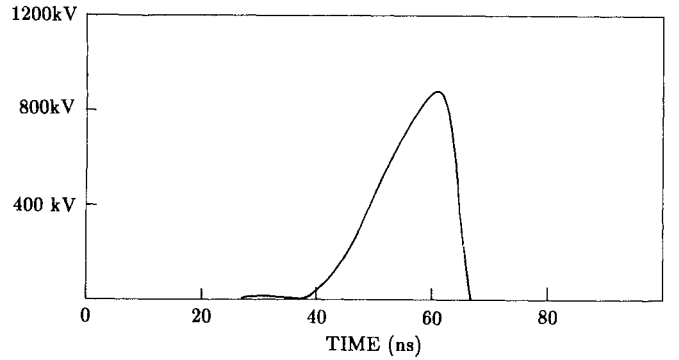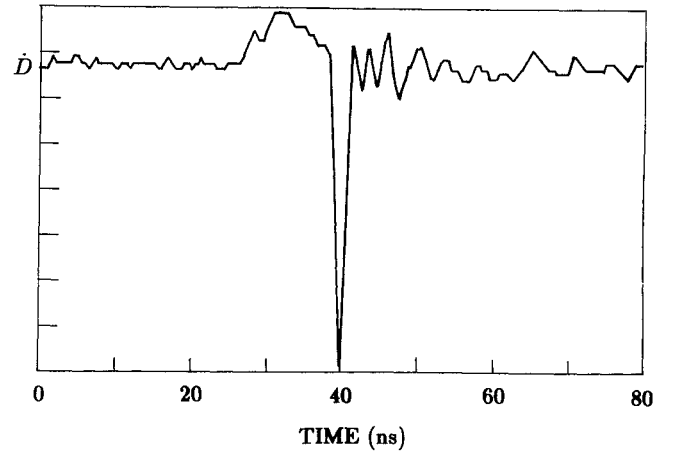$$\bar{v} = 8.8 \ V^{0.6} \ t_{eff}^{-1/2} \qquad (1)$$

where

Figure 3. $\dot{D}$ probe measurement of output switch.

$\bar{v}[cm/\mu s] \ \equiv$ average streamer velocity.

$V[MV] \ \equiv$ gap voltage.

$t_{eff}[\mu s] \ \equiv$ time where the electric field is greater than 63% of the maximum field.

The gap for a given voltage is then

$$d = 8.8 \ V^{0.6} \ t_{eff}^{1/2} \ . \qquad (2)$$

For an assumed linear ramp, t_{eff} for the output switch is approximately 0.011 μs.

At 1 MV, the gap would be 0.922 cm. The gap for the above shot was 0.9 cm. An expected number of current channels, where a channel is defined as carrying greater than 45% of the current carried by the first channel to form, can be calculated with the relationship developed by Martin for multi-channel gaps. That is

$$2\delta(t) = 0.1(\tau_L + \tau_R) + 0.8 \ \tau_{tran} \ , \qquad (3)$$

where

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$\delta(t) \equiv$ standard deviation of the time of closure of the gap on a rising pulse

$\tau_L = \dfrac{L}{nZ}$, inductive portion of the pulse risetime

$\tau_R = \dfrac{5}{n^{1/3}Z^{1/3}E^{4/3}}$, resistive portion of the pulse risetime

$\tau_{tran} = \dfrac{\ell\sqrt{\epsilon_r}}{nc}$, wave transit time between channels

$n \equiv$ the number of channels

$L \equiv$ arc inductance

$Z \equiv$ impedance driving the gap.

Because the channels were only isolated by 0.6 ns, for an assumed conservative voltage jitter of 3%[7] and a linear voltage rise, seven channels would be expected. Eight pins were provided on the output switch. Although the shot shown above had a 10–90% current rise time of 2.5 ns, some shots were observed to have risetimes of 1.5 ns $(0.5-1\times10^{14}\text{A/S})$. There is some shot-to-shot variation in the number of current channels produced. Early efforts were made to compare a continuous edge gap to an array of points in terms of channel stabilization. These were abandoned due to difficulty in maintaining a uniform gap. Figure 4 shows an open shutter photograph of the intermediate and output switch discharges. Note how some of the pins have branched discharges. Also note the relatively uniform intensity of the channels.
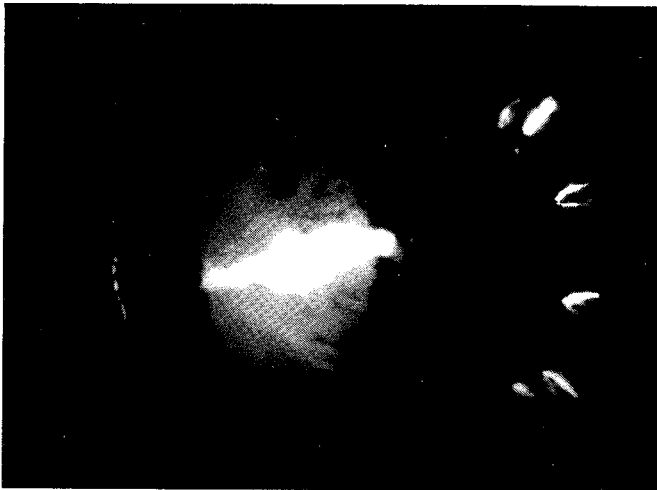

Figure 4. Open shutter photograph of switch discharges.

During testing, unusual phenomena were observed. A circulating pump was run continuously to maintain water resistivity (>18 MΩ-cm). No attempt was made to control temperature. Tens of degrees fahrenheit temperature increases resulted in the need to reduce the primary voltage to 45 kV to avoid prefiring of the multi-channel switch. For slow repetitive testing, improvements in switch performance occurred as the shot count increased. This was attributed to a self adjustment of the switch gap due to erosion of the pins. During the 5 Hz

testing (usually 150 second bursts), the $\dot{D}$ signal was sampled at a 1 Hz rate. Degraded switch performance was observed and was compensated for by increasing the primary voltage during the burst. This implies, again, that erosion of the electrodes was significant over 100's of shots.

Conclusion

We have demonstrated multi-channel repetitive switching with water at 5 Hz and 1 MV for 150 second bursts. Energy transfer per pulse is on the order of 1 kJ.

The stated repetitive limits were due to the power supply current limitation. Longer bursts[8] and higher rates[9] may be possible, but there was insufficient time to verify this. Apparently increased fluid temperature reduces the breakdown strength of water at MV/cm stress levels or increases the gap voltage through variation of the water dielectric constant. This can be verified by an experiment more suitable for studying such effects. Finally, significant erosion occurs during a burst with stainless steel electrodes. This erosion may be minimized with the use of Cu-W and less enhancement of the electrodes. Recent tests have shown less than 0.25 mm of length erosion after thousands of shots with elkonite pins.

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